U.S. NUCLEAR REGULATORY COMMISSION

STANDARD REVIEW PLAN

OFFICE OF NUCLEAR REACTOR REGULATION

3.9.2 DYNAMIC TESTING AND ANALYSIS OF SYSTEMS, COMPONENTS, AND EQUIPMENT

REVIEW RESPONSIBILITIES

Primary - Mechanical Engineering Branch (MEB)

Secondary - None

I. AREAS OF REVIEW

MEB reviews the criteria, testing procedures, and dynamic analyses employed to assure the structural and functional integrity of piping systems, mechanical equipment, reactor internals, and their supports under vibratory loadings, including those due to fluid flow and postulated seismic events to assure conformance with General Design Criteria 1, 2, 4, 14 and 15. The staff review covers the following specific areas:

1. Piping vibration, thermal expansion, and dynamic effect testing should be conducted during startup testing. The systems to be monitored should include (a) all ASME Code Class 1, 2, and 3 systems, (b) other high-energy piping systems inside Seismic Category I Structures, (c) high-energy portions of systems whose failure could reduce the functioning of any Seismic Category I plant feature to an unacceptable safety level, and (d) Seismic Category I portions of moderate-energy piping systems located outside containment. The supports and restraints necessary for operation during the life of the plant are considered to be parts of the piping system. The purpose of these tests is to confirm that these piping systems, restraints, components, and supports have been adequately designed to withstand flow-induced dynamic loadings under the steady-state and operational transient conditions anticipated during service and to confirm that normal thermal motion is not restrained. The test program description should include a list of different flow modes, a list of selected locations for visual inspections and other measurements, the acceptance criteria, and possible corrective actions if excessive vibration or indications of normal thermal motion restraint occurs.

2. The following areas related to the seismic system analysis described in the applicant's safety analysis report (SAR) are reviewed.

a. <u>Seismic Analysis Method</u>

For all Category I systems, components, equipment and their supports (including supports for conduit and cable trays, and ventilation ducts), the applicable seismic analysis methods (response spectra, time history, equivalent static load) are reviewed. The manner in which the dynamic system analysis method is performed is reviewed. The method chosen for selection of significant modes and an adequate number of masses or degrees or freedom is reviewed. The manner in which consideration is given in the seismic dynamic analysis to maximum relative displacements between supports is reviewed. In addition, other significant effects that are accounted for in the dynamic seismic analysis such as hydrodynamic effects and nonlinear response are reviewed.

b. <u>Determination of Number of Earthquake Cycles</u>

Criteria or procedures used to establish the number of earthquake cycles during one seismic event and the maximum number of cycles for which applicable Category I systems and components are designed are specified by Structural Engineering Branch (SEB) in SRP Section 3.7.3, subsection I.2.

c. <u>Basis for Selection of Frequencies</u>

As applicable, criteria or procedures used to separate fundamental frequencies of components and equipment from the forcing frequencies of the support structure are reviewed.

d. <u>Three Components of Earthquake Motion</u>

The procedures by which the three components of earthquake motion are considered in determining the seismic response of systems, and components are reviewed.

e. <u>Combination of Modal Responses</u>

When a response spectrum approach is used for calculating the seismic response of systems, or components, the phase relationship between various modes is lost. Only the maximum responses for each mode can be determined. The maximum responses for modes do not in general occur at the same time and these responses have to be combined according to some procedure selected to approximate or bound the response of the system. When a response spectra method is used, the description of the procedure for combining modal responses (shears, moments, stresses, deflections, and accelerations) is reviewed, including that for modes with closely spaced frequencies.

f. <u>Analytical Procedures for Piping Systems</u>

The analytical procedures applicable to seismic analysis of piping systems, including methods used to consider differential piping support movements at different support points located within a structure and between structures, are reviewed.

g. <u>Multiply-Supported Equipment and Components with Distinct Inputs</u>

The criteria and procedures for seimic analysis of equipment and components supported at different elevations within a building and between buildings with distinct inputs are reviewed.

h. <u>Use of Constant Vertical Static Factors</u>

Where applicable, justification for the use of constant static factors as vertical response loads for designing Category I systems, components, equipment and their supports in lieu of the use of a vertical seismic system dynamic analysis is reviewed.

i. <u>Torsional Effects of Eccentric Masses</u>

The criteria and procedures that are used to consider the torsional effects of eccentric masses (e.g., valve operators) in seismic system analyses are reviewed.

j. <u>Category I Buried Piping Systems</u>

For Category I buried piping, the seismic criteria and methods which consider the effect of fill settlement including pipe profile and pipe stresses, the movements at support points, penetrations, and anchors are reviewed.

k. <u>Interaction of Other Piping With Category I Piping</u>

The seismic analysis procedures to account for the seismic motion of non-Category I piping systems in the seismic design of Category I piping are reviewed.

l. <u>Criteria Used for Damping</u>

The criteria to account for damping in systems, components, equipment and their supports is reviewed.

3. Dynamic responses of structural components within the reactor vessel caused by steady-state and operational flow transient conditions should be analyzed for prototype (first of a design) reactors. Generally, this analysis is not required for nonprototypes except that segments of an analysis may be necessary if there are substantial deviations from the prototype internals design. The purpose of this analysis is to predict the vibration behavior of the components, so that the input forcing functions and the level of response can be estimated. Before conducting the analyses, the specific locations for calculated responses, the considerations in defining the mathematical models, the interpretation of analytical results, the acceptance criteria, and the methods of verifying predictions by means of tests should be determined. If the reactor internal structures are a nonprototype design, reference should be made to the results of tests and analyses for the prototype reactor and a brief summary of the results should be given.

4. Flow-induced vibration testing of reactor internals should be conducted during the preoperational and startup test program. The purpose of this test is to demonstrate that flow-induced vibrations similar to those expected during operation will not cause unanticipated flow-induced

vibrations of significant magnitude or structural damage. The test program description should include a list of flow modes, a list of sensor types and locations, a description of test procedures and methods to be used to process and interpret the measured data, a description of the visual inspections to be made, and a comparison of the test results with the analytical predictions. If the reactor internal structures are a nonprototype design, reference should be made to the results of tests and analyses for the prototype reactor and a brief summary of the results should be given.

5. Dynamic system analyses should be performed to confirm the structural design adequacy and ability, with no loss of function, of the reactor internals and unbroken loops of the reactor coolant piping to withstand the loads from a loss-of-coolant accident (LOCA) in combination with the SSE. The staff review covers the methods of analysis, the considerations in defining the mathematical models, the descriptions of the forcing functions, the calculational scheme, the acceptance criteria, and the interpretation of analytical results.

6. A discussion should be provided which describes the methods to be used to correlate results from the reactor internals vibration test with the analytical results from dynamic analyses of the reactor internals under steady-state and operational flow transient conditions.

   In addition, test results from previous plants of similar characteristics may be used to verify the mathematical models used for the loading condition of LOCA in combination with the SSE by comparing such dynamic characteristics as the natural frequencies. The staff review covers the methods to be used for comparison of test and analytical results and for verification of the analytical models.

Computer programs used in the analyses discussed in this SRP section are reviewed in accordance with SRP Section 3.9.1.

The Reactor Systems Branch (RSB) verifies on request that (1) the various flow modes to be used to conduct the vibration test of the reactor internals are representative of the steady-state and operational transient conditions anticipated for the reactor during its service, and (2) that an acceptable hydraulic analysis has been used to determine the loads acting on the reactor coolant system piping and the reactor internals.

II. ACCEPTANCE CRITERIA

MEB acceptance criteria are based on meeting the relevant requirements set forth in General Design Criteria 1, 2, 4, 14 and 15. The relevant requirements are as follows:

A. General Design Criterion 1, as it relates to the testing and analysis of systems, components, and equipment with appropriate safety functions being performed to appropriate quality standards.

B. General Design Criterion 2, as it relates to systems, components, and equipment important to safety being designed to withstand appropriate combinations of the effects of normal and accident conditions with the effects of natural phenomena (SSE).

C. General Design Criterion 4, as it relates to systems and components important to safety being appropriately protected against the dynamic effects of discharging fluids.

D. General Design Criterion 14, as it relates to systems and components of the reactor coolant pressure boundary being designed so as to have an extremely low probability of rapidly propagating failure or of gross rupture.

E. General Design Criterion 15, as it relates to the reactor coolant system being designed with sufficient margin to assure that the reactor coolant pressure boundary will not be breeched during normal operating conditions including anticipated operational occurrences.

Specific criteria necessary to meet the relevant requirements of the Commission regulations identified above are as follows:

1. Relevant requirements of GDC 14 and 15 are met if vibration, thermal expansion, and dynamic effects testing are conducted during startup functional testing for specified high-and moderate-energy piping, and their supports and restraints. The purpose of these tests is to confirm that the piping, components, restraints, and supports have been designed to withstand the dynamic loadings and operational transient conditions that will be encountered during service as required by the Code and to confirm that no unacceptable restraint of normal thermal motion occurs.

   An acceptable test program to confirm the adequacy of the designs should consist of the following:

   a. A list of systems that will be monitored.

   b. A listing of the different flow modes of operation and transients such as pump trips, valve closures, etc. to which the components will be subjected during the test. (For additional guidance see Reference 8.) For example, the transients associated with the reactor coolant system heatup tests should include, but not necessarily be limited to:

      (1) Reactor coolant pump start.

      (2) Reactor coolant pump trip.

      (3) Operation of pressure-relieving valves.

      (4) Closure of a turbine stop valve.

   c. A list of selected locations in the piping system at which visual inspections and measurements (as needed) will be performed during the tests. For each of these selected locations, the deflection (peak-to-peak) or other appropriate criteria, to be used to show that the stress and fatigue limits are within the design levels, should be provided.

   d. A list of snubbers on systems which experience sufficient thermal movement to measure snubber travel from cold to hot position.

e. A description of the thermal motion monitoring program, i.e., verification of snubber movement, adequate clearances and gaps, including acceptance criteria and how motion will be measured.

f. If vibration is noted beyond the acceptance levels set by the criteria of c., above, corrective restraints should be designed, incorporated in the piping system analysis, and installed. If, during the test, piping system restraints are determined to be inadequate or are damaged, corrective restraints should be installed and another test should be performed to determine that the vibrations have been reduced to an acceptable level. If no snubber piston travel is measured at those stations indicated in d., above, a description should be provided of the corrective action to be taken to assure that the snubber is operable.

2. To meet the relevant requirements of GDC 2, the acceptance criteria for the areas of review described in subsection I.2 of this SRP section are given below. Other approaches which can be justified to be equivalent to or more conservative than the stated acceptance criteria may be used to confirm the ability of all seismic Category I systems, components, equipment, and their supports to function as needed during and after an earthquake.

a. <u>Seismic Analysis Methods</u>

The seismic analysis of all Category I systems, components, equipment, and their supports (including supports for conduit and cable trays and ventilation ducts) should utilize either a suitable dynamic analysis method or an equivalent static load method, if justified.

(1) <u>Dynamic Analysis Method</u>

A dynamic analysis (e.g., response spectrum method, time history method, etc.) should be used when the use of the equivalent static load method cannot be justified. To be acceptable such analyses should consider the following items:

(a) Use of either the time history method or the response spectrum method.

(b) Use of an adequate number of masses or degrees of freedom in dynamic modeling to determine the response of all Category I and applicable non-Category I systems and plant equipment. The number is considered adequate when additional degrees of freedom do not result in more than a 10% <u>increase</u> in responses. Alternately, the number of degrees of freedom may be taken equal to twice the number of modes with frequencies less than 33 hz.

(c) Investigation of a sufficient number of modes to assure participation of all significant modes. The criterion for sufficiency is that the inclusion of additional modes does not result in more than a 10% <u>increase</u> in responses.

(d) Consideration of maximum relative displacements among supports of Category I systems, and components.

(e) Inclusion of significant effects such as piping interactions, externally applied structural restraints, hydrodynamic (both mass and stiffness effects) loads, and nonlinear responses.

(2) <u>Equilvalent Static Load Method</u>

An equilvalent static load method is acceptable if:

(a) Justification is provided that the system can be realistically represented by a simple model and the method produces conservative results in terms of responses. Typical examples or published results for similar systems may be submitted in support of the use of the simplified method.

(b) The design and associated simplified analysis account for the relative motion between all points of support.

(c) To obtain an equivalent static load of equipment or component which can be represented by a simple model, a factor of 1.5 is applied to the peak acceleration of the applicable floor response spectrum. A factor of less than 1.5 may be used if adequate justification is provided.

In addition, for equipment which can be modeled adequately as a one-degree-of-freedom system, the use of a static load equivalent to the peak of the floor response spectra is acceptable. For piping supported at only two points, the use of a static load equivalent to the peak of the floor response spectra is also acceptable.

b. <u>Determination of Number of Earthquake Cycles</u>

During the plant life at least one safe shutdown earthquake (SSE) and five operating basis earthquakes (OBE) should be assumed. The number of cycles per earthquake should be obtained from the synthetic time history (with a minimum duration of 10 seconds) used for the system analysis, or a minimum of 10 maximum stress cycles per earthquake may be assumed (extract from SRP Section 3.7.3, subsection II.2).

c. <u>Basis for Selection of Frequencies</u>

To avoid resonance, the fundamental frequencies of components and equipment should preferably be selected to be less than 1/2 or more than twice the dominant frequencies of the support structure. Use of equipment frequencies within this range is acceptable if the equipment is adequately designed for the applicable loads.

d. Three Components of Earthquake Motion

Depending upon what basic methods are used in the seismic analysis, i.e., response spectra or time history method, the following two approaches are considered acceptable for the combination of three-dimensional earthquake effects. (Ref. 11, 12, and 13)

(1) Response Spectra Method

When the response spectra method is adopted for seismic analysis, the maximum structural responses due to each of the three components of earthquake motion should be combined by taking the square root of the sum of the squares of the maximum codirectional responses caused by each of the three components of earthquake motion at a particular point of the structure or of the mathematical model.

(2) Time History Analysis Method

When the time history analysis method is employed for seismic analysis, two types of analysis are generally performed depending on the complexity of the problem. (a) to obtain maximum responses due to each of the three components of the earthquake motion: in this case the method for combining the three-dimensional effects is identical to that described in (a) except that the maximum responses are calculated using the time history method instead of the spectrum method. (b) To obtain time history responses from each of the three components of the earthquake motion and combine them at each time step algebraically: the maximum response in this case can be obtained from the combined time solution. When this method is used, to be acceptable, the earthquake motions specified in the three different directions should be statistically independent.

e. Combination of Modal Responses

When the response spectrum method of analysis is used to determine the dynamic response of damped linear systems, the most probable response is obtained as the square root of the sum of the squares of the responses from individual modes. Thus, the most probable system response, R, is given by

$$R = \left(\sum_{k=1}^{N} R_k^2\right)^{1/2} \qquad (1)$$

where R_k is the response for the k^{th} mode and N is the number of significant modes considered in the modal response combination.

When modes with closely spaced modal frequencies exist, an acceptable method for obtaining the system response is to take the absolute sum of the responses of the closely spaced modes and combine this sum with other remaining modal responses using the square root of the sum of the squares rule. Two modes having frequencies within 10% of each other are considered as modes with closely spaced frequencies.

This approach is simple and straightforward in all those cases where the group of modes with closely spaced frequencies is tightly bundled, i.e., the lowest and the highest modes of the group are within 10% of each other. However, when the group of closely spaced modes is spaced widely over the frequency range of interest (while the frequencies of the adjacent modes are closely spaced), the absolute sum method of combining responses tends to yield over-conservative results. To obviate this problem, a general approach applicable to all modes is considered appropriate. The following equation is merely a mathematical representation of this approach.

The most probable system response, R, is given by

$$R = \left(\sum_{k=1}^{N} R_k^2 + 2 \sum \left| R_\ell R_m \right| \right)^{1/2} \qquad (2)$$

Where the second summation is to be done on all ℓ and m modes whose frequencies are closely spaced to each other.

Other approaches which give an equivalent degree of conservatism to the above methods, and which are adequately justified are also acceptable. Regulatory Guide 1.92 (Reference 10) "Combining Modal Responses and Spatial Components in Seismic Response Analysis" presents detailed guidance on this topic.

f. Analytical Procedures for Piping Systems

The seismic analysis of Category I piping may use either a dynamic analysis or an equivalent static load method. The acceptance criteria for the dynamic analysis or equivalent static load methods are as given in subsection II.2.a of this SRP section.

g. Multiply-Supported Equipment and Components With Distinct Inputs

Equipment and components in some cases are supported at several points by either a single structure or two separate structures. The motions of the primary structure or structures at each of the support points may be quite different.

A conservative and acceptable approach for equipment items supported at two or more locations is to use an upper bound envelope of all the individual response spectra for these locations to calculate maximum inertial responses of multiply-supported items. In addition, the relative displacements at the support points should be considered. Conventional static analysis procedures are acceptable for this purpose. The maximum relative support displacements can be obtained from the structural response calculations or, as a conservative approximation, by using the floor response spectra. For the latter option, the maximum displacement of each support is predicted by $S_d = S_a g/\omega^2$, where S_a is the spectral acceleration in "g's" at the high frequency end of the spectrum curve (which, in turn, is equal to the maximum floor acceleration), g is the gravity constant, and ω is the fundamental frequency of the primary support structure in radians per second. The support displacements can then be imposed on the supported item in the most unfavorable combination. The responses due to the inertia effect and relative displacements should be combined by the absolute sum method.

In the case of multiple supports located in a single structure, an alternate acceptable method using the floor response spectra involves determination of dynamic responses due to the worst single floor response spectrum selected from a set of floor response spectra obtained at various floors and applied identically to all the floors, provided there is no significant shift in frequencies of the spectra peaks. In addition, the support displacements should be imposed on the supported item in the most unfavorable combination using static analysis procedures.

In lieu of the response spectrum approach, time histories of support motions may be used as excitations to the systems (Ref. 16). Because of the increased analytical effort compared to the response spectrum techniques, usually only a major equipment system would warrant a time history approach. The time history approach does, however, provide more realistic results in some cases as compared to the response spectrum envelope method for multiply-supported systems.

h. <u>Use of Constant Vertical Static Factors</u>

The use of constant vertical load factors as vertical response loads for the seismic design of all Category I systems, components, equipment, and their supports in lieu of the use of a vertical seismic system dynamic analysis is acceptable only if it can be justified that the structure is rigid in the vertical direction. The criterion for rigidity is that the lowest frequency in the vertical direction is more than 33 hz.

i. <u>Torsional Effects of Eccentric Masses</u>

For seismic Category I systems, if the torsional effect of an eccentric mass such as a valve operator in a piping system is judged to be significant, the eccentric mass and its eccentricity should be included in the mathematical mode. The criteria for significance will have to be determined on a case-by-case basis.

j. <u>Category I Buried Piping Systems</u>

For Category I buried piping systems, the following items should be considered in the analysis:

(1) The inertial effects due to an earthquake upon buried piping systems should be adequately accounted for in the analysis. Use of the procedures described in References 11 and 14 is acceptable.

(2) The effects of static resistance of the surrounding soil on piping deformations or displacements, differential movements of piping anchors, bent geometry and curvature changes, etc., should be adequately considered. Use of the procedures described in Reference 15 is acceptable.

(3) When applicable, the effects due to local soil settlements, soil arching, etc., should also be considered in the analysis.

k. Interaction of Other Piping with Category I Piping

To be acceptable, each non-Category I piping system should be designed to be isolated from any Category I piping system by either a constraint or barrier, or should be remotely located with regard to the seismic Category I piping system. If it is not feasible or practical to isolate the Category I piping system, adjacent non-Category I piping should be analyzed according to the same seismic criteria as applicable to the Category I piping system. For non-Category I piping systems attached to Category I piping systems, the dynamic effects of the non-Category I piping should be simulated in the modeling of the Category I piping. The attached non-Category I piping, up to the first anchor beyond the interface, should also be designed in such a manner that during an earthquake of SSE intensity it will not cause a failure of the Category I piping.

l. Criteria Used for Damping

Regulatory Guide 1.61 (Reference 9) "Damping Values for Seismic Design of Nuclear Power Plants," provides acceptable values which may be used. The use of alternate damping values requires justification.

3. Relevant requirements of GDC 1 and 4 are met as given below. The following guidelines, in addition to Regulatory Guide 1.20 (Reference 7), apply to the analytical solutions to predict vibrations of reactor internals for prototype plants. Generally, this analysis is required only for prototype designs.

a. The results of vibration calculations for a prototype reactor should consist of the following:

(1) Dynamic responses to operating transients at critical locations of the internal structures should be determined and, in particular, at the locations where vibration sensors will be mounted on the reactor internals. For each location, the maximum response, the modal contribution to the total response, and the response causing the maximum stress amplitude should be calculated.

(2) The dynamic properties of internal structures, including the natural frequencies, the dominant mode shapes, and the damping factors should be characterized. If analyses are performed on a component structural element basis, the existence of dynamic coupling among component structure elements should be investigated.

(3) The response characteristics, such as the dependence on hydrodynamic excitation forces, the flow path configuration, coolant recirculation pump frequencies, and the natural frequencies of the internal structures, should be identified.

(4) Acceptance criteria for allowable responses should be established, as should criteria for the location of vibration sensors. Such criteria should be related to the Code allowable stresses, strains, and limits of deflection that are established to preclude loss of function with respect to the reactor core structures and fuel assemblies.

b. The forcing functions should account for the effects of transient flow conditions and the frequency content. Acceptable methods for formulating forcing functions for vibration prediction include the following:

(1) Analytical method: based on standard hydrodynamic theory, the governing differential equations for vibratory motions should be developed and solutions obtained with appropriate boundary conditions and parameters. This method is acceptable where the geometry along the fluid flow paths is mathematically tractable.

(2) Test-analysis combination method: based on data obtained from plant tests or scaled model tests (e.g., velocity or pressure distribution data), forcing functions should be formulated which will include the effects of complex flow path configurations and wide variations of pressure distributions.

(3) Response-deduction method: based on a derivation of response characteristics from plant or scaled model test data, forcing functions should be formulated. However, since such functions may not be unique, the computational procedures and the basis for the selection of the representative forcing functions should be described.

c. Acceptable methods of obtaining dynamic responses for vibration predictions are as follows:

(1) Force-response computations are acceptable if the characteristics of the forcing functions are predetermined on a conservative basis and the mathematical model of the reactor internals is appropriately representative of the design.

(2) If the forcing functions are not predetermined, either a special analysis of the response signals measured from reactor internals of similar design may be performed to predict amplitude and modal contributions, or parameter studies useful for extrapolating the results from tests of internals or components of similar designs based on composite statistics may be used.

d. Vibration predictions should be verified by test results. If the test results differ substantially from the predicted response behavior, the vibration analysis should be appropriately modified to improve the agreement with test results and to validate the analytical method as appropriate for predicting responses of the prototype unit, as well as of other units where confirmatory tests are to be conducted.

4. Relevant requirements of GDC 1 and 4 are met as given below. The preoperational vibration test program for the internals of a prototype (first of a design) reactor should conform to the requirements for a prototype test, as specified in Regulatory Guide 1.20, including vibration prediction, vibration monitoring, data reduction, and surface inspection. The test program to demonstrate design adequacy of the reactor internals should include, but not necessarily be limited to the following:

   a. The vibration testing should be conducted with the fuel elements in the core or with dummy elements which provide equivalent dynamic effects and flow characteristics. Testing without fuel elements in the core may be acceptable if it can be demonstrated that testing in this mode is conservative.

   b. A brief description of the vibration monitoring instrumentation should be provided, including instrument types and diagrams of locations, which should include the locations having the most severe vibratory motions or having the most effect on safety functions.

   c. The planned duration of the test for the normal operation modes to assure that all critical components are subjected to at least 10^6 cycles of vibration should be provided. For instance, if the lowest response frequency of the core internal structures is 10 Hz, a total test duration of 1.2 days or more will be acceptable.

   d. Testing should include all of the different flow modes of normal operation and upset transients. The proposed set of flow modes are acceptable if they provide a conservative basis for determining the dynamic response of the reactor internals and are reviewed by RSB on request.

   e. The methods and procedures to be used to process the test data to obtain a meaningful interpretation of the core structure vibration behavior should be provided. Vibration interpretation should include the amplitude, frequency content, stress state, and the possible effects on safety functions.

   f. Vibration predictions, test acceptance criteria and bases, and permissible deviations from the criteria should be provided before the test.

   g. Visual and nondestructive surface inspections should be performed after the completion of the vibration tests. The inspection program description should include the areas subject to inspection, the methods of inspection, the design access provisions to the reactor internals, and the equipment to be used for performing such inspections. These inspections should be conducted preferably following the removal of the internals from the reactor vessel. Where removal is not feasible, the inspections should be performed by means of equipment appropriate for in situ inspection. The areas inspected should include all load-bearing interfaces, core restraint devices, high stress locations, and locations critical to safety functions.

For internals of subsequent reactors that have the same design, size, configuration, and operating conditions as the prototype reactor internals, the vibration test program should conform to the requirements of the appropriate nonprototype program as specified in Regulatory Guide 1.20.

5. Relevant requirements of GDC 2 and 4 are met as given below. Dynamic system analyses should be performed to confirm the structural design adequacy of the reactor internals and the reactor coolant piping (unbroken loops) to withstand the dynamic loadings of the most severe LOCA in combination with the SSE. Where a substantial separation between the forcing frequencies of the LOCA (or SSE) loading and the natural frequencies of the internal structures can be demonstrated, the analysis may treat the loadings statically.

   The most severe dynamic effects from LOCA loadings are generally found to result from a postulated double-ended rupture of a primary coolant loop near a reactor vessel inlet or outlet nozzle with the reactor in the most critical normal operating mode. However, all other postulated break locations should be evaluated and the location producing the controlling effects should be identified.

   Mathematical models used for dynamic system analysis for LOCA in combination with the SSE effects should include the following:

   a. Modeling should include reactor internals and dynamically related piping, pipe supports, components, and fluid-structure interaction effects when applicable. Typical diagrams and the basis of modeling should be developed and described.

   b. Mathematical models should be representative of system structural characteristics, such as the flexibility, mass inertia effect, geometric configuration, and damping (including possible coexistence of viscous and Coulomb damping).

   c. Any system structural partitioning and directional decoupling employed in the dynamic system modeling should be justified.

   d. The effects of flow upon the mass and flexibility properties of the system should be discussed.

   Typical diagrams and the basis for postulating the LOCA-induced forcing function should be provided, including a description of the governing hydrodynamic equations and the assumptions used for mathematically tractable flow path geometries, tests for determining flow coefficients, and any semiempirical formulations and scaled model flow testing for determining pressure differentials or velocity distributions. The acceptabilty of the hydraulic analysis, as reviewed by RSB on request, is based on established engineering practice and generic topical reviews performed by the staff.

The methods and procedures used for dynamic system analyses should be described, including the governing equations of motion and the computational scheme used to derive results. Time domain forced-response computation is acceptable for both LOCA and SSE analyses. The response spectrum modal analysis method may be used for SSE analysis.

The stability of elements in compression, such as the core barrel and the control rod guide tubes under outlet pipe rupture loadings should be investigated.

Either response spectra or time histories may be used for specifying seismic input motions of the SSE at the reactor core supports.

The criteria for acceptance of the analytical results are as provided in SRP Sections 3.9.3 and 3.9.5.

6. Relevant requirements of GDC 1 are met as given below. Regarding the correlation to be made of tests and analyses of reactor internals, a discussion covering the following items to assure the adequacy and sufficiency of the test and analysis results should be provided:

   a. Comparison of the measured response frequencies with the analytically obtained natural frequencies of the reactor internals for possible verification of the mathematical model used in the analysis.

   b. Comparison of the analytically obtained mode shapes with the shape of measured motion for possible identification of the modal combination or verification of a specific mode.

   c. Comparison of the response amplitude time variation and the frequency content obtained from test and analysis for possible verification of the postulated forcing function.

   d. Comparison of the maximum responses obtained from test and analysis for possible verification of stress levels.

   e. Comparison of the mathematical model used for dynamic system analysis under operational flow transients and under the combined LOCA and SSE loadings, to note similarities.

III. REVIEW PROCEDURES

The reviewer will select and emphasize material from the procedures described below, as may be appropriate for a particular case.

General Design Criteria 1, 2, 4, 14, and 15 state that all structures, system and components important to safety should be designed and tested to assure that safety functions can be performed in the event of operational transients, earthquakes, and LOCA loadings.

Under these guidelines, the staff reviews the treatment of dynamic responses of safety-related piping systems and reactor internal structures by the following procedures:

1. During the CP stage, the PSAR is reviewed to assure that the applicant has provided a commitment to conduct a piping steady-state vibration, thermal expansion and operational transient test program. The applicants program description should be sufficiently comprehensive to contain all the elements of an acceptable program as described in subsection II.1 of this SRP Section.

   During the OL stage, the FSAR is reviewed to assure that the applicant's PSAR commitment is fulfilled and the program is developed in sufficient detail. The reviewer should be assured that the applicants program as described in Sections 3.9.2 and 14.0 of the FSAR is sufficiently developed to:

   a. Establish the rationale and bases for the acceptance criteria and selection of locations to monitor pipe motions.

   b. Provide the displacement or other appropriate limits at locations to be monitored.

   c. Describe the techniques and instruments (as needed) for monitoring or measuring pipe motions.

   d. Assure that the NRC will be provided documentation of any corrective action resulting from the test and conformation by additional testing that substantiates effectiveness of the corrective action.

2. For seismic system analysis review, the following review procedures are implemented.

   a. <u>Seismic Analysis Methods</u>

   For all Category I systems, components, equipment and their supports (including supports for conduit and cable trays, and ventilation ducts), the applicable methods of seismic analysis (response spectra, time history, equivalent static load) are reviewed to ascertain that the techniques employed are in accordance with the acceptance criteria as given in subsection II.2.a of this SRP section.

   b. <u>Determination of Number of Earthquake Cycles</u>

   Criteria or procedures used to establish the number of earthquake cycles are reviewed to determine that they are in accordance with the acceptance criteria as given in subsection II.2.b of this SRP section. Justification for deviating from the acceptance criteria is requested from the applicant, as necessary.

   c. <u>Basis for Selection of Frequencies</u>

   As applicable, criteria or procedures used to separate fundamental frequencies of components and equipment from the forcing frequencies of the support structure are reviewed to determine compliance with the acceptance criteria of subsection II.2.c of this SRP section.

   d. <u>Three Components of Earthquake Motion</u>

   The procedures by which the three components of earthquake motion are considered in determining the seismic response of systems are reviewed to determine compliance with the acceptance criteria of subsection II.2.d of this SRP section.

e. Combination of Modal Responses

The procedures for combining modal responses are reviewed to determine compliance with the acceptance criteria of subsection II.2.e of this SRP section, when a response spectrum modal analysis method is used.

f. Analytical Procedures for Piping Systems

For all Category I piping and applicable non-Category I piping, the methods of seismic analysis (response spectra, time history, equivalent static load) are reviewed to determine that the techniques employed are in accordance with the acceptance criteria of subsection II.2.f of this SRP section. Typical mathematical models are reviewed to judge whether all significant degrees of freedom have been included.

g. Multiply-Supported Equipment and Components With Distinct Inputs

The criteria for the seismic analysis of multiply-supported components and equipment with distinct inputs are reviewed to determine that the criteria are in accordance with the acceptance criteria of subsection II.2.g of this SRP section.

h. Use of Constant Vertical Static Factors

Use of constant static factors as response loads in the vertical direction for the seismic design of any Category I systems in lieu of a detailed dynamic method is reviewed to determine that constant static factors are used only if the structure is rigid in the vertical direction based on the definition for rigidity given in subsection II.2.h of this SRP section.

i. Torsional Effects of Eccentric Masses

The procedures for seismic analysis of Category I piping systems are reviewed to determine compliance with the acceptance criteria of subsection II.2.i of this SRP section.

j. Category I Buried Piping Systems

The analysis procedures for Category I buried piping are reviewed to determine that they are in accordance with the acceptance criteria of subsection II.2.j of this SRP section. This includes review of the procedures used to consider the effect of fill settlement including pipe profile and pipe stresses, and the differential movements at support points, penetrations, and anchors. Any procedures that are not adequately justified are so identified and the applicant is requested to provide additional justification.

k. <u>Interaction of Other Piping with Category I Piping</u>

The criteria used to design the interfaces between Category I and non-Category I piping are reviewed to determine compliance with the acceptance criteria of subsection II.2.k of this SRP section.

l. <u>Criteria used for Damping</u>

The criteria used to account for damping in systems, components, equipment and their supports is reviewed to determine that it is in accordance with the regulatory position in Reference 9.

3. At the CP stage, the applicant should commit to performing an analysis of the vibration of the reactor internal structures if they are designated as a prototype design. A brief description of the methods and procedures to be used for the analysis should be provided.

At the OL stage, a detailed dynamic analysis should be provided for a prototype design, to be used for vibration prediction prior to the performance of preoperational vibration tests. Acceptance of the analysis is based on the technical soundness of the analytical method and procedures used and the degree of conformance to the acceptance criteria listed above. In addition, the analysis is verified by correlation with the test results when these are available.

For both CP and OL stages, if the reactor internal structures are a non-prototype design, then reference should be made to the reactor which is prototypical of the reactor being reviewed. A brief summary of test and analysis results for the prototype should be given. Alternatively, the information may be contained in another applicable document, such as a topical report, to which reference should be made.

4. At the CP stage, the staff review of the program for preoperational vibration testing of reactor internals for flow-induced vibrations includes the following matters:

a. The applicant should clarify his intention to perform either a prototype test or a non-prototype test.

b. If the plant is designated as a prototype, a brief description of the preoperational vibration test program should be provided. The staff review will be based on the conformance of this program to the requirements as listed in subsection II.4, above.

c. If the plant is a non-prototype, the applicant should identify the existing plant of similar design that is the prototype plant. The staff reviews the validity of the designated prototype, including any design difference of reactor internal structures from the prototype plant to verify that any design modifications do not substantially alter the behavior of the flow transients and the response of the reactor internals. Additional detailed analysis, scaled model tests, or installation of some instrumentation during the confirmatory test may be required in order to complete the review. In addition, the applicant should commit to performing the prototype test if adequate test results are not obtained on a timely basis for the designated prototype.

At the OL stage, the staff review includes the following procedures:

(1) A detailed preoperational vibration test program and the tentative schedule to perform the test are reviewed. If elements of the program differ substantially from the guidelines specified in Regulatory Guide 1.20, discussion of the need and justification for the differences should be given. On request, RSB verifies that the flow modes to be used are acceptable.

(2) For a prototype plant, the review covers the acceptability of vibration prediction, the visual surface inspection procedures, the details of instrumentation for vibration monitoring, the methods and procedures to process the test results, and possible supplementary tests, such as component vibration tests, flow tests, and scaled model tests.

(3) For a nonprototype plant, the staff verifies the applicability of the designated prototype, including the design similarity of the reactor internal structures to the prototype. Additional detailed analysis, scaled model tests, or vibration monitoring in the confirmatory tests may be needed in order to complete the review.

5. In the CP stage review of the dynamic analysis of the reactor internals and unbroken loops of the reactor coolant piping under faulted condition loadings, the applicant commits to perform this analysis or identifies the applicable document, generally in the form of a topical report, containing the required information. A brief description of the scope and methods of analysis should be provided.

   In the OL review, the staff reviews the detailed information to confirm that an adequate analysis has been made of the capability of reactor internal structures and unbroken loops to withstand dynamic loads from the most severe LOCA in combination with the safe shutdown earthquake. The staff review covers the analytical methods and procedures, the basis of the forcing functions, the mathematical models to represent the dynamic system, and the stability investigations for the core barrel and essential compressive elements. Acceptance of the analysis is based on (1) the technical soundness of the analytical methods used, (2) the degree of conformance to the acceptance criteria listed above, and (3) verification that stresses under the combined loads are within allowable limits of the applicable code and deformations are within the limits set to assure the ability of reactor internal structures and piping to perform needed safety functions. On request, RSB verifies that an acceptable hydraulic analysis has been used.

6. MEB reviews the program which the applicant has committed to implement as part of the preoperational test procedure, principally to correlate the test measurements with the analytically predicted flow-induced dynamic response of the reactor internals. MEB reviews the applicant's statements in this area to assure that there is a commitment to submit a report on a timely basis. The report should summarize the analyses and test results so that MEB can review the compatibility of the results from tests and analyses, the consistency between mathematical models used for different loadings, and the validity of the interpretation of the test and analysis results.

IV. EVALUATION FINDINGS

The reviewer verifies that sufficient information has been provided and that the review supports conclusions of the following type, to be included in the staff's safety evaluation report:

The staff concludes that the dynamic testing and analysis of systems, components, and equipment is acceptable and meets the relevant requirements of General Design Criteria 1, 2, 4, 14 and 15. This conclusion is based on the following:

1. The applicant has met the relevant requirements of General Design Criteria 14 and 15 with respect to the design and testing of the reactor coolant pressure boundary to assure that there is a low probability of rapidly propagating failure and of gross rupture and to assure that design conditions are not exceeded during normal operation including anticipated operational occurrences by having an acceptable vibration, thermal expansion, and dynamic effects test program which will be conducted during startup and initial operation on specified high- and moderate-energy piping, and all associated systems, restraints and supports. The tests provide adequate assurance that the piping and piping restraints of the system have been designed to withstand vibrational dynamic effects due to valve closures, pump trips, and other operating modes associated with the design basis flow conditions. In addition, the tests provide assurance that adequate clearances and free movement of snubbers exist for unrestrained thermal movement of piping and supports during normal system heatup and cooldown operations. The planned tests will develop loads similar to those experienced during reactor operation.

2. The applicant has met the relevant requirements of General Design Criteria 2 with respect to demonstrating design adequacy of all Category I systems, components, equipment and their supports to withstand earthquakes by meeting the regulatory positions of Regulatory Guides 1.61 and 1.92 and by providing an acceptable seismic systems analysis procedure and criteria. The scope of review of the seismic system analysis included the seismic analysis methods of all Category I systems, components, equipment and their supports. It included review of procedures for modeling, inclusion of torsional effects, seismic analysis of Category I piping systems, seismic analysis of multiply-supported equipment and components with distinct inputs, justification for the use of constant vertical static factors and determination of composite damping. The review has included design criteria and procedures for evaluation of the interaction of non-Category I piping with Category I piping. The review has also included criteria and seismic analysis procedures for reactor internals and Category I buried piping outside containment.

   The system analyses are performed by the applicant on an elastic basis. Modal response spectrum multidegree of freedom and time history methods form the bases for the analyses of all major Category I systems, components, equipment and their supports. When the modal response spectrum method is used, governing response parameters are combined by the square root of the sum of the squares rule. However, the absolute sum of the modal responses are used for modes with closely spaced frequencies. The square root of the sum of the squares of the maximum codirectional responses is used in accounting for three components of the earthquake motion for both the time history and response spectrum methods. Floor spectra inputs to be used for design and test verifications of systems, components, equipment and their supports are generated from the time history method, taking into account variation of parameters by peak widening. A vertical seismic system dynamic analysis will be employed for all systems, and components, equipment and their supports where analyses show significant structural amplification in the vertical direction.

3. The applicant has met the relevant requirements of General Design Criteria 1 and 4 with respect to the reactor internals being designed and tested to quality standard commensurate with the importance of the safety functions being performed and being appropriately protected against dynamic effects by meeting the regulatory positions of Regulatory Guide 1.20 for the conduct of preoperational vibration tests and by having a preoperational vibration program planned for the reactor internals which provides an acceptable basis for verifying the design adequacy of these internals under test loading conditions comparable to those that will be experienced during operation. The combination of tests, predictive analysis, and post-test inspection provide adequate assurance that the reactor internals will, during their service lifetime, withstand the flow-induced vibrations of reactor operation without loss of structural integrity. The integrity of the reactor internals in service is essential to assure the proper positioning of reactor fuel assemblies and unimpaired operation of the control rod assemblies to permit safe reactor operation and shutdown.

4. The applicant has met the relevant requirements of General Design Criteria 2 and 4 with respect to the design of systems and components important to safety to withstand the effects of earthquakes and the appropriate combinations of the effects of normal and postulated accident conditions with the effects of the safe shutdown earthquake (SSE) by having a dynamic system analysis to be performed which provides an acceptable basis for confirming the structural design adequacy of the reactor internals and unbroken piping loops to withstand the combined dynamic loads of postulated loss of coolant accidents (LOCA) and the SSE and the combined loads of a postulated main steam line rupture and SSE (for a BWR). The analysis provides adequate assurance that the combined stresses and strains in the components of the reactor coolant system and reactor internals will not exceed the allowable design stress and strain limits for the materials of construction, and that the resulting deflections or displacements at any structural elements of the reactor internals will not distort the reactor internals geometry to the extent that core cooling may be impaired. The methods used for component analysis have been found to be compatible with those used for the systems analysis. The proposed combinations of component and system analyses are, therefore, acceptable. The assurance of structural integrity of the reactor internals under LOCA conditions for the most adverse postulated loading event provides added confidence that the design will withstand a spectrum of lesser pipe breaks and seismic loading events.

5. The applicant has met the relevant requirements of General Design Criterion 1 with respect to systems and components being designed and tested to quality standards commensurate with the importance of the safety functions to be performed by the proposed program to correlate the test measurements with the analysis results. The program constitute an acceptable basis for demonstrating the compatibility of the results from tests and analyses, the consistency between mathematical models used for different loadings, and the validity of the interpretation of the test and analysis results.

   For the FSAR, the review should provide justification for a finding similar to that stated above with the phrase "will be implemented" modified to read "has been implemented."

V. IMPLEMENTATION

The following is intended to provide guidance to applicants and licensees regarding the NRC staff's plans for using this SRP section. Except in those cases in which the applicant proposes an acceptable alternative method for complying with specified portions of the Commission's regulations, the method described herein will be used by the staff in its evaluation of conformance with Commission regulations.

Implementation schedules for conformance to parts of the method discussed herein are contained in the referenced Regulatory Guides.

VI. REFERENCES

1. 10 CFR Part 50, Appendix A, General Design Criterion 1, "Quality Standards and Records."

2. 10 CFR Part 50, Appendix A, General Design Criterion 2, "Design Bases for Protection Against Natural Phenomena."

3. 10 CFR Part 50, Appendix A, General Design Criterion 4, "Environmental and Missile Design Bases."

4. 10 CFR Part 50, Appendix A, General Design Criterion 14, "Reactor Coolant Pressure Boundary."

5. 10 CFR Part 50, Appendix A, General Design Criterion 15, "Reactor Coolant System Design."

6. ASME Boiler and Pressure Vessel Code, Section III, "Nuclear Power Plant Components," American Society of Mechanical Engineers.

7. Regulatory Guide 1.20, "Comprehensive Vibration Assessment Program for Reactor Internals During Preoperational and Initial Startup Testing."

8. Regulatory Guide 1.68, "Preoperational and Initial Startup Test Programs for Water-Cooled Power Reactors."

9. Regulatory Guide 1.61, "Damping Values for Seismic Design of Nuclear Power Plants."

10. Regulatory Guide 1.92, "Combining Modal Responses and Spatial Components in Seismic Response Analysis."

11. N. M. Newmark, J. A. Blume, and K. K. Kapur, "Design Response Spectra for Nuclear Power Plants," Journal of the Power Division, American Society of Civil Engineers, pp. 287-303, November 1973.

12. S. L. Chu, M. Amin, and S. Singh, "Spectral Treatment of Actions of Three Earthquake Components on Structures," Nuclear Engineering and Design, Vol. 21, pp. 126-136 (1972).

13. N. M. Newmark and E. Rosenblueth, "Fundamentals of Earthquake Engineering," Prentice Hall, (1971).

14. N. M. Newmark, "Earthquake Response Analysis of Reactor Structures," Nuclear Engineering and Design, Vol. 20, pp. 303-322 (1972).

15. M. Hetenyi, "Beams on Elastic Foundation," The University of Michigan Press (1946).

16. R. P. Kassawara, and D. A. Peck, "Dynamic Analysis of Structural Systems Excited at Multiple Support Locations," 2nd ASCE Specialty Confrerence on Structural Design of Nuclear Plant Facilities, Chicago, Dec. 17-18, 1973.